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Battery Compartment Design Guidelines for Equipment Using Lithium-Sulfur Dioxide Batteries

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13. ABSTRACT *(Maximum 200 words)*
This Technical Bulletin (TB) provides guidelines for the proper design and test of battery compartments housing lithium-sulfur dioxide (LiSO2) batteries to minimize injuries as a result of violent battery ventings. A description of LiSO2 batteries and associated hazards is included to inform the reader why these battery compartments may be necessary. Also addressed is the risk assesssment process and evaluation parameters for determining if a battery compartment designed and tested in accordance with this TB is required. Battery compartment design recommendations to minimize equipment damage and injury as a result of violent ventings that may occur when the batteries are installed in equipment are addressed in detail. Equipment design recommendations are also provided to minimize the chances of a violent battery incident from occurring when installed in the equipment. Test guidelines, including determination of test pressures and proper use of associated formulas, are included.

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Table of Contents

List of Figures

List of Tables

List of Equations

Acronyms

AAE	Army Acquisition Executive
AMC	Army Materiel Command
CDD	Complete Discharge Device
C-E	Communications - Electronics
CECOM	Communications Electronics Command
COTS	Commercial Off-The-Shelf
DSRM	Directorate of Safety Risk Management
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FY	Fiscal Year
IAW	In Accordance With
LED	Light Emitting Diode
$LiSO_2$	Lithium Sulfur Dioxide
MILES	Multiple Laser Engagement System
PEO	Program Executive Office
PM	Program Manager
PSI	Pounds per Square Inch
RAC	Risk Assessment Code
REV	Revision
SAWE	Simulated Area Weapons Effects
SINCGARS	Single Channel Ground and Air Radio System
SOC	State of Charge
SOCI	State of Charge Indicator
SO_2	Sulfur Dioxide
SSRA	System Safety Risk Assessment
TB	Technical Bulletin
TBD	To Be Determined

Foreword

The information in this TB is presented in several sections which are arranged to facilitate use of the TB. Section 1 describes the background of this TB as well as lithium sulfur dioxide batteries and associated hazards. Section 2 provides the risk assessment process and evaluation parameters to determine if battery compartments designed and tested In Accordance With (IAW) this TB are required. Section 3 provides battery compartment design recommendations to minimize equipment damage and personal injury as a result of violent battery ventings. Section 4 provides equipment design recommendations to minimize the chances of a violent battery incident from occurring. Section 5 provides test guidelines and procedures. Section 6 provides a synopsis and additional information. The steps in designing and testing battery compartments are provided in Appendix A. Sample safety requirements for equipment utilizing $LiSO_2$ batteries are provided in Appendix B. Appendix C provides examples on how to properly use equations to determine test criteria.

SECTION 1 Introduction

1.1 Background

Technical Bulletin number 7 (TB-7) was developed by CECOM in the late 1980's as a result of violent incidents experienced with the use of Lithium Sulfur Dioxide ($LiSO_2$) batteries in Communications-Electronics (C-E) equipment.[1] TB-7 provided guidelines for the proper design and test of battery compartments housing $LiSO_2$ batteries to minimize injuries as a result of such incidents. The TB has been updated to include lessons learned, incidents involving injury and complete system loss, new battery features, and examples to show how to correctly apply formulas for determining test criteria for single and multiple battery applications.

Recent injuries from incidents have shown the importance of a properly designed $LiSO_2$ battery compartment as well as the need to ensure that the equipment to be powered from the batteries is properly designed. This update addresses how to maximize equipment safety by incorporating a properly designed and tested battery compartment as well as discussing how to minimize poorly designed equipment. It is essential that consideration be given to the possible use of a battery compartment early in the system design phase when $LiSO_2$ batteries are being considered as a power source. This will minimize costly design changes, if at a later stage it is determined that a battery compartment able to successfully pass pressure testing is required.

1.2 A Description of $LiSO_2$ batteries

$LiSO_2$ batteries are composed of one or more cells connected in series. The required battery voltage and capacity determines the number of battery cells necessary. Some batteries contain two cell strings which can be externally connected either in series or parallel. For example, the BA-5590/U (see figure 1.1) has two 15 volt strings that can be placed in series to

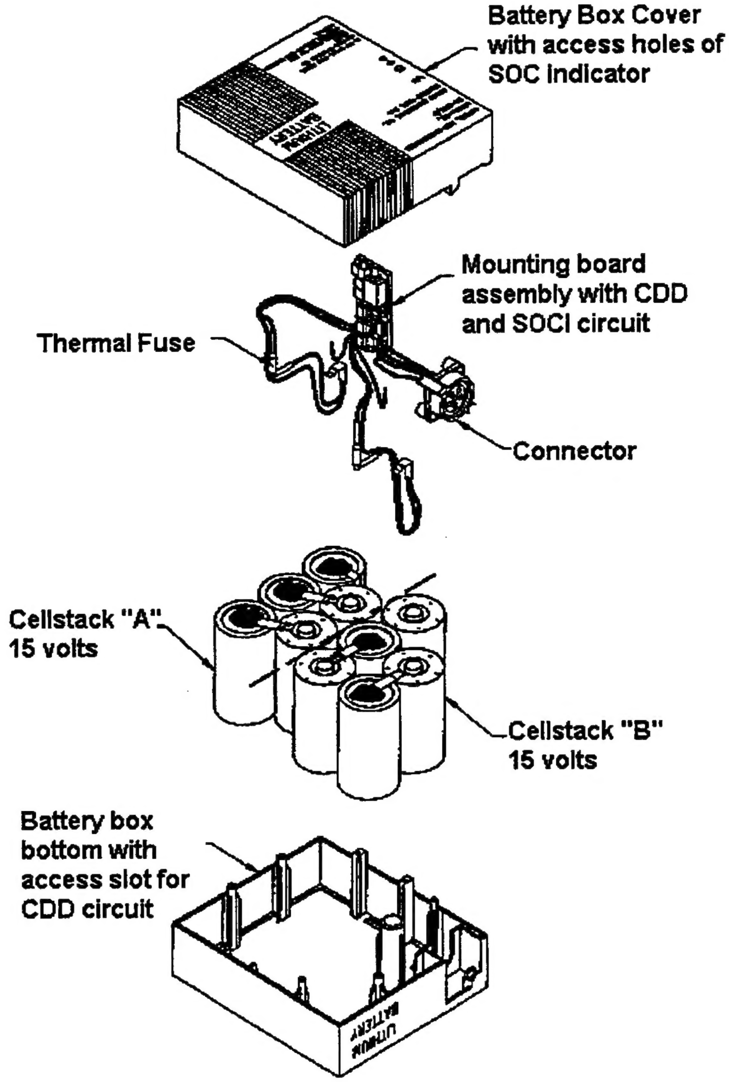

Figure 1.1. BA-5590/U

[1] Ref. 1, TB 7.

yield a 30 volt output, or in parallel to yield 15 volts with twice the capacity and current output. All Army multicell $LiSO_2$ batteries contain diodes to prevent charging, and Complete Discharge Devices (CDDs) to allow battery disposal as nonhazardous material after usage and activation of the CDD. In the future, several $LiSO_2$ batteries will be fitted with State of Charge (SOC) indicators to allow the user to determine remaining battery capacity with the simple push of a button. All battery cells contain a venting mechanism, which is designed to open up when the internal cell pressure reaches a critical value. See table 1.1 for a summary of the features of CECOM $LiSO_2$ batteries. Refer to MIL-PRF-49471 for the specification sheets for each of the batteries.[2] Refer to TB 43-0134 for disposition and disposal information on these batteries.[3]

Table 1.1 CECOM $LiSO_2$ Battery Features

Nomenclature	Type (Note 1)	QTY Cells	Safety Features (Note 2)	CDD (Note 3)	SOCI (Note 4)	Voltage
BA-5847A/U (Note 5)	Rec	2	X	X	N/A	6
BA-5847B/U (Note 6)	Rec	2	X	X	N/A	6
BA-5847C/U (Note 5)	Rec	2	X	X	X	6
BA-5599/U	Rec	3	X	X	N/A	9
BA-5599A/U	Rec	3	X	X	X	9
BA-5112/U	Rec	4	X	X	N/A	12
BA-5112A/U	Rec	4	X	X	N/A	12
BA-5598/U	Rec	5	X	X	N/A	3/15
BA-5598A/U	Rec	5	X	X	X	3/15
BA-5588/U	Rec	5	X	X	N/A	15
BA-5588A/U	Rec	5	X	X	X	15
BA-5093/U	Rec	9	X	X	N/A	27
BA-5093A/U	Rec	9	X	X	N/A	27
BA-5557/U	Rec	10	X	X	N/A	15/30
BA-5557A/U	Rec	10	X	X	X	15/30
BA-5590/U	Rec	10	X	X	N/A	15/30
BA-5590A/U	Rec	10	X	X	X	15/30
BA-5567/U	Cyl	1	N/A	N/A	N/A	3
BA-5567A/U	Cyl	1	N/A	N/A	N/A	3
BA-5600/U	Cyl	3	X	X	N/A	9
BA-5800/U	Cyl	2	X	X	N/A	6

KEY:

Note (1) Rectangular (Rec) and Cylindrical (Cyl) battery types.

Note (2) Safety Features include overcurrent protection (electrical fuse), overtemperature protection (thermal fuse), and charge protection (diode). All batteries, including the BA-5567 utilize cell vents.

Note (3) Complete Discharge Device (CDD) is used to reduce the amount of active lithium to permit disposal as nonhazardous material. The CDD consists of a resistor and switch. Resistor is connected across cell string, bypassing all safety features. N/A=quantity of lithium is less than .5g per battery.

Note (4) State Of Charge Indicator (SOCI) provides % of remaining battery capacity in four ranges. Consists of a momentary switch and display (two green LEDS).

Note (5) These batteries contain F cells.

Note (6) This battery uses a pull-out type of CDD, different than the normal push activated switch. This battery uses the D cell and has a lower capacity than the BA-5847A and C.

[2] Ref. 2, MIL-PRF-49471.

[3] Ref. 3, TB 43-0134.

1.3 A Description of $LiSO_2$ Battery Cells

Each $LiSO_2$ battery utilizes a cell design which incorporates a venting mechanism (coined area) in the cell container (either on the end or side of the cell depending on the manufacturer). These vents are intended to safely relieve internal cell pressures when reaching approximately 400 +/- 50 pounds per square inch (psi). Pressure buildups can be caused by a battery or cell defect and/or external abnormal stress (excessive heating) or abuse of the battery. To date, whenever a multicell $LiSO_2$ battery has vented, only one cell has been involved. This is due to the fact that when one cell vents, the battery electrically shuts off as designed.

1.3.1. End Cap Cell Vents

These cells tend to fail by the separation of one of the cell ends from the rest of the cell as shown in Figure 1.2. During the venting of the cell, the pressure will be directed axially from the cell.

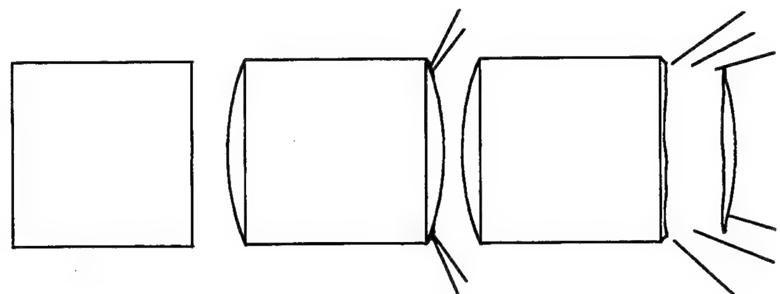

Figure 1.2. Steps in Violent Venting of an End Cell Vent

1.3.2 Side Vent Cells

These cells tend to fail by separation of the metal along the entire length of the coined area, then continues to tear the metal to both ends of the cell as shown in Figure 1.3.

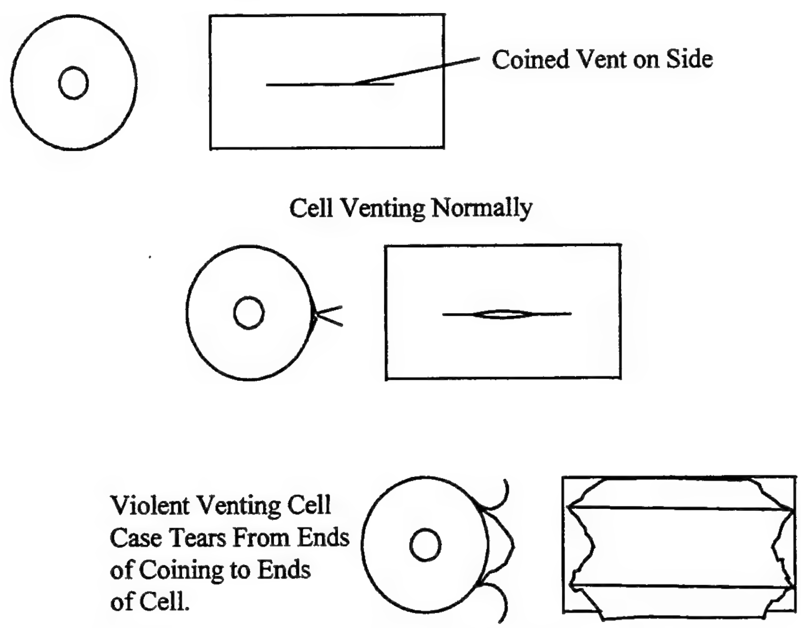

Figure 1.3. Steps in Violent Venting of Side Vent Cell

1.4 Types of $LiSO_2$ Battery Incidents

$LiSO_2$ batteries can vent under certain conditions. The severity of the ventings from the field has varied greatly; they have ranged from very mild to very violent, or explosive. Battery compartments must be designed to protect against mild and violent ventings. The following definitions are provided for cell ventings which can be grouped into three types, characterized by varying severity of the ventings.

1.4.1 Mild Venting

This type of venting is caused by the slow rise of pressure due to an increase in temperature in a cell to the point where the built-in pressure relief mechanism opens as intended and relieves the pressure by a relatively slow release of the SO_2 in the cell. The user may hear a hissing sound and will usually smell sulfur dioxide gas, which has a sharp, acrid odor and has been characterized by some people as smelling like "rotten eggs." The internal cell temperature rise may be attributed to excessive environmental heating or from high temperatures produced during discharge.

1.4.2 Violent Venting

This type of venting is caused when the internal temperature/pressure of a faulty cell rises so rapidly that the built-in pressure relief mechanism cannot relieve the pressure fast enough and the cell bursts and fragments, and releases a large amount of gas almost instantly. Violent ventings can also be caused by excessive environmental heating or from deep discharge caused by poorly designed equipment. This TB provides guidelines on how to minimize injury as a result of a violent venting.

1.4.3 Lithium Explosion

This event is even more severe than a violent venting, and is caused by faulty equipment design or improper equipment use/abuse which results in a partially discharged battery being charged. CECOM $LiSO_2$ batteries have diodes to prevent charging, but diodes are known to break down under certain conditions, such as prolonged and/or elevated storage temperatures. Therefore, if a voltage is applied to a partially discharged battery that contains such a diode, the battery may explode.

This TB is not intended to establish design guidelines to protect personnel in the event of a lithium explosion. Provided the equipment is properly designed and built, and that the equipment is not misused, there should be essentially no chance of charging, which may result in a lithium explosion.

1.5 Alternate Battery Considerations

The use of $LiSO_2$ batteries is expected to be gradually phased out in favor of other primary battery chemistries, such as lithium manganese dioxide, or secondary (rechargeable) battery chemistries. Therefore, considerations must be made with regard to which batteries may be available in the future and the possible modifications that may be required for safe implementation.

SECTION 2. Risk Assessment

2.1 Introduction

Injuries have occurred as a result of rupture and fragmentation of $LiSO_2$ batteries, $LiSO_2$ battery compartments, and equipment, during violent ventings and explosions of $LiSO_2$ batteries. Therefore, to prevent injuries, it may be necessary for equipment utilizing $LiSO_2$ batteries to have compartments designed and tested IAW this TB. The responsible official, IAW AR 385-16, must make an informed decision to determine if such a battery compartment must be implemented and tested.[4] The following section addresses the risk assessment process in which this decision should be based.

2.2 Incident History

The rate of all $LiSO_2$ battery violent ventings reported from FY 86 through FY 97 is approximately 1/125,000 (note that explosions and mild ventings are not covered in this rate). Therefore, this rate shall be used in any risk assessment regarding violent ventings of $LiSO_2$ batteries when installed in equipment.

2.3 Risk Assessment

The risk associated with a violent venting of an $LiSO_2$ battery in a particular piece of equipment is evaluated IAW MIL-STD-882C to determine probability and severity of an occurrence.[5] Probability can be categorized as frequent, probable, occasional, remote, and improbable. The categories for severity can be catastrophic, critical, marginal, and negligible. Probability and severity are combined to form the Risk Assessment Code (RAC) which is used to determine the risk level the hazard presents (see table 2.1). A comprehensive system safety risk assessment has been prepared on a system utilizing BA-5590 batteries and is a good reference document in support of the risk assessment process.[6]

To determine the appropriate RAC, the following factors must be considered by the evaluator of the equipment utilizing $LiSO_2$ batteries in order to accurately assess and quantify the hazard associated with the use of these batteries with regard to both equipment damage and injury:

- *If the equipment is portable, how the equipment is carried and the location of the battery compartment in relation to the user.*

- *How the equipment is used. For example, during use, does the battery compartment face away from the user? Also, how close is the battery compartment to the user, and to what part of the body?*

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[4] Ref. 4, AR 385-16.

[5] Ref. 5, MIL-STD-882C

[6] Ref. 6, System Safety Risk Assessment

Table 2.1. Risk Assessment Codes

FREQUENCY OF OCCURRENCE	HAZARD CATEGORIES I CATASTROPHIC	II CRITICAL	III MARGINAL	IV NEGLIGIBLE
(A) FREQUENT	1A	2A	3A	**4A**
(B) PROBABLE	1B	2B	**3B**	4B
(C) OCCASIONAL	1C	2C	**3C**	4C
(D) REMOTE	1D	**2D**	3D	4D
(E) IMPROBABLE	**1E**	2E	3E	4E

RISK LEVEL	HAZARD RISK INDEX	DECISION AUTHORITY
HIGH	1A,1B,1C,2A,2B,3A,1D,2C	AAE OR DESIGNEE
MEDIUM	1E,2D,3C,3B,4A	PEO OR EQUIVALENT
LOW	2E,3D,3E,4B,4C,4D,4E	PM OR EQUIVALENT

- *The number of battery cells and the cell size. The bigger the battery cell, the more dangerous the venting can be.*

- *Utilization of battery charging circuitry in the equipment which could place an external voltage across an $LiSO_2$ battery. (NOTE: Properly designed equipment will NOT place an external voltage on the $LiSO_2$ battery terminals).*

- *Number of systems to be fielded and the total number of batteries to be used over the life of the system.*

- *Utilization of a voltage cutoff to shut off the equipment when the batteries no longer provide sufficient power for operation. This will prevent batteries from being overdischarged, which will minimize ventings.*

2.4 Risk Resolution

Based on the RAC, not all hazards are severe enough or occur often enough to warrant the expenditures required to eliminate or control them. The level of the risk that is assigned to the particular system utilizing $LiSO_2$ batteries will determine if battery compartment testing is required, and the proper decision authority (see table 2.1) to accept the risk that may remain.

2.5 Successful Battery Compartment Testing

Battery compartments must be tested to 150% of the design pressure. A successful test is one in which there is no shattering of the battery compartment or the expulsion of the battery or any pieces of the battery compartment (including any parts of the equipment interfacing the battery compartment). The potential safety hazard with respect to violent ventings has been adequately controlled when a compartment passes testing (i.e., a non-residual hazard). No further action would be required.

2.6 Battery Compartment Test Failure

To adequately resolve a battery compartment test failure, the following must be performed:

- *Redesign the battery compartment and retest or*

- *Accept the risk at the appropriate risk acceptance authority level as a residual hazard. (NOTE: The hazard level can be adjusted following test failure. For example, if the test failure is not catastrophic (i.e., compartment does not shatter and/or battery does not fly out of the compartment), an initially medium level hazard could possibly be lowered to a low level hazard. In this case the PM could accept the hazard without redesigning the battery compartment.)*

SECTION 3 Battery Compartment

3.1 Why Battery Compartments are Necessary

$LiSO_2$ batteries are designed to meet the power and logistical requirements of C-E equipment used by the military. These batteries provide higher capacity, higher current, and longer operating life; they are lighter, and have a longer shelf life than other primary batteries presently available. Although CECOM $LiSO_2$ batteries have been designed to provide maximum safety during use, certain abusive conditions can cause the batteries to exhibit unique explosive types of hazards, such as violent ventings. A violent venting is the sudden and violent release of the battery cell contents. Due to the destructive power of a violent venting, properly designed and tested battery compartments may be necessary to minimize injury from flying equipment and battery parts.

3.2 Battery Compartment Requirements

The battery compartment must be able to safely release 150% of the maximum pressure (calculated using the formulas provided in section 5.3) which can be generated during a violent battery venting without the compartment shattering, fragmenting, releasing batteries, or allowing any parts to "fly" off the equipment. The containment of the vented gases within the battery compartment is not practical and is potentially unsafe since the gases could escape immediately upon opening of the battery compartment for battery replacement.

$LiSO_2$ battery compartments designed IAW this TB will minimize injury from mild and violent ventings, but not lithium explosions. To design the battery compartment to safely handle lithium explosions would make the equipment too heavy to carry. Additionally, battery explosions are rare and, to date, have only occurred from charging such as when external power and charging circuitry are not properly implemented. Battery explosions can be easily prevented by an equipment design that does not allow external charging of the $LiSO_2$ battery.

Battery cell vents are designed to open at approximately 400 +/- 50 psi to safely relieve any pressure buildup due to overheating or other abusive conditions. As previously discussed, the vents are generally of two types: end and side vents. Therefore, depending on the particular cell design, the pressures can increase the destructive power in certain directions. For cells with end vents, as shown in Figure 1.2, damage during a venting could be done by the axial pressure caused by the deformation of the cell ends even before the actual failure and venting of the cell. During the venting of the cell, the pressure would continue to be directed axially from the cell. As shown in figure 1.3, during the venting of a cell with a side vent, the pressure would be directed perpendicular from the cell. It should be noted that different battery manufacturers may orient cells differently in the same battery type. It is therefore very difficult to predict which direction the gas will flow during a violent venting of each battery type. This means that all sides of the battery compartment must be equally strengthened to resist failure due to violent ventings of a battery with either end or side vent cells. During pressure testing, the gas flow will be directed along both axes. Furthermore, the 150% safety factor will determine if all walls are able to withstand a venting.

3.3 Battery Compartment Design Considerations

It should be noted that there is no ideal design for a battery compartment; each equipment should use design features which best meet its requirements. The recommended steps to follow for successful design and testing of $LiSO_2$ battery compartments is provided in Appendix A.

If it is determined, through the System Safety Risk Assessment process, that equipments using $LiSO_2$ batteries do not require a battery compartment designed or tested IAW this TB, the compartment must still be able to safely release gas during a venting. For example, the use of a screw cap type of lid may be able to safely relieve the pressure buildup when the compartment is opened to replace the batteries.

3.3.1 Free Volume

It has been estimated that in less than 5 milliseconds one violently venting "D" cell will release gas that, if allowed to expand to atmospheric pressure, would occupy 30-40 cubic feet (or 850,000-1,133,000 cc). When confined in a battery compartment the pressure would be high, hence the problem. The smaller the free volume in the battery compartment, the higher the pressure.

Many of the newer equipments are small hand-held units which utilize cylindrical batteries such as the BA-5800/U and BA-5600/U. These two battery types are made up of either two or three D cells packaged in line. Consequently the battery packaging is very efficient and there is practically no free volume in the battery itself. The equipments typically house these batteries in a battery compartment which is also cylindrical in shape and has very little net free volume when the battery is installed. This results in very high pressures in the battery compartment.

3.3.1.1 Methods to Increase Free Volume

Implementation of the following will decrease the pressures within the battery compartment:

- Enlarge battery compartment. Added free volume in the battery compartment does lower the pressure within the compartment, but limited space and design of the equipment may limit the amount of free volume that can be made available.

- Utilize rectangular batteries which have more free volume (i.e., space between the cylindrical cells). However, limited space and equipment design may not allow a larger battery.

- Open the battery compartment to the volume in the electronics portion of the equipment, thus adding this volume to that in the battery compartment, and providing more total volume for the gases to expand into. The opening between the two compartments may likely have to be

sealed in some manner to provide environmental protection to the electronics compartment as well as EMC-EMI protection. This closure then breaks away during a violent venting, making the additional volume available. One equipment that used this approach initially had a readout window in the electronics compartment which blew out during a venting, which constituted a failure. The equipment was subsequently modified so that the openings into the electronics compartment were sized to restrict the amount of gases passing into the electronics compartment, thus relieving the pressure on the readout window. The window seal was also strengthened and subsequently passed testing.

3.3.1.2 Precautions of Increasing Free Volume When Using the Internal Electronics

The following precautions must be considered with equipment designs that use the electronics compartment as additional free volume:

- *Realize that the equipment will be subjected to the high vent pressures and may need to be reinforced.*

- *Displays may shatter causing a test failure.*

- *Any configuration changes to the equipment (i.e., additional circuit cards, resistors, etc.) that could impact the flow of gases into the equipment would require retesting.*

- *The opening between the battery compartment and the electronics compartment must be large enough to provide a suitable mechanism to vent battery gases.*

3.3.2 Containment of Pressure

The goal when designing a battery compartment is to safely vent or release the pressures generated during a violent venting, and not to contain the gas generated. The containment of the vented gas is possible, but not practicable, since the compartment would have to be so heavily built that the equipment would no longer be soldier portable (small and lightweight). In addition, the pressurized gas will pose a hazard to the operator when opening the compartment for battery replacement, etc.

It may be necessary to have some other venting means present in a battery compartment to allow pressure equalization (i.e., air transport) or to allow gases that are released in a "mild" venting to escape to the outside without damaging the equipment. Equipments in use today that were designed before the advent of $LiSO_2$ batteries may have vents conforming to MIL-V-55341. These vents are designed to open at pressures on the order of 2 psi, so that the hydrogen gas liberated by magnesium batteries in use at that time would be safely vented, and not infiltrate into the equipment where it could be ignited. The valve has only a fraction of 1 square inch of venting area, which is useless in venting the amounts of gas liberated in a violent venting. This valve may be useful however in venting the gases liberated in a normal "mild" venting without

damaging the battery compartment. (NOTE: These vent valves alone are NOT capable of safely relieving the pressures associated with a violent venting. Additionally, these vents may not provide an adequate seal to meet immersion requirements.)

3.3.3 Material

The following sections address materials that have been used in previous battery compartment designs.

3.3.3.1 Die Cast Aluminum

Die cast aluminum is NOT recommended for $LiSO_2$ battery compartments since it is too brittle (having an elongation of 5 percent or less) and compartments made of this material almost never pass pressure testing. Die cast aluminum battery compartments typically have elongations on the order of 3 to 4%, which means they give very little before they break. Alloy 443 has an elongation of 9% but has a yield strength of about one third of the other alloys. Alloy 518 has an elongation of 8% and an acceptable yield strength but has poor fluidity, which makes it difficult to properly fill molds with thin sections. Battery compartments made of alloy 380 have exhibited failure at the corners between two sides, where the bulging of the sides due to the internal pressure has caused the metal to fracture due to the bending stresses.

3.3.3.2 Wrought Aluminum

This material has been successfully used in battery compartment design. This type of aluminum, which usually comes in the form of sheet stock, is much more ductile and tougher than die cast aluminum. That is, it bends but does not easily break. It has the disadvantage of requiring more separate steps in its fabrication, to arrive at the finished product. The basic battery compartment can be made by deep drawing, or by cutting and welding. If heavier areas are required, such as for the mounting of fasteners or ribbing for stiffening, additional pieces have to be welded or riveted on, or separate steps performed to further form the material.

3.3.3.3 Unreinforced Plastics

These materials have worked well in several battery compartment designs. Unreinforced plastics are plastics that are entirely one material. These plastics tend to have a low modulus of elasticity, therefore bending easily. They can also have quite high elongations. Xenoy, which exhibits excellent properties for use in a battery compartment, has an elongation of 135%. This flexibility is good from the standpoint of venting gases, but there are other design requirements where this flexibility can cause problems. This will be discussed further in section 3.4. It should be noted that the material thickness and mold designs/injections play a critical factor in overall elasticity.

Most unreinforced plastics are nonconductive and therefore may require some type of conductive coating to meet the equipment's EMI/EMC and TEMPEST requirements.

3.3.3.4 Reinforced Plastics

Reinforced plastics are plastics that are comprised of a meltable plastic commingled with other materials such as glass fibers which are much more rigid and of higher tensile strength. As the amount of reinforcing material increases, the combination has greater rigidity, and higher yield strength, but much lower elongation, becoming more brittle. Caution must be used when selecting this material as a potential battery compartment material.

Most reinforced plastics have the same coating requirements as unreinforced plastics regarding EMI/EMC and TEMPEST.

3.3.4 Battery Compartment Closures

The means used to close the battery compartment is a design component of major importance. During normal operation of the equipment, the battery compartment closure must hold the compartment securely in place and may be required to meet water immersion requirements. During a violent venting, the closures must not fail and allow the battery compartment and battery to fly away from the equipment. The battery compartment and environmental requirements must be balanced so that compliance with one requirement does not preclude compliance with the other.

A common means of failure in plastic compartments is at the point of attachment of catches to the compartment. The stresses concentrated at these points may be of sufficient magnitude to cause local deformation of the plastic and the fastener, or the fastener insert (i.e., threaded) could come out of the plastic. Excessive temperatures may also contribute to failure due to softening of the plastic. The use of inserts in any battery compartment material is not a good design practice since they could also pull out during a venting, causing a failure.

3.4 Successful Battery Compartment Designs

Several compartment designs which successfully passed the violent venting test used the mechanism of allowing the battery compartment to separate sufficiently from its mating gasketed surface to provide an opening through which the gas could escape. The catches used in these designs had to have sufficient spring-loaded travel to allow this separation, and sufficient strength at the end of this travel to stop further separation. There are catches which have no spring-loaded travel, some that have small amounts, and some that have considerable travel. A battery compartment with catches must allow the battery compartment to separate from the mating equipment a distance sufficient for the compartment to come out of the equipment fence surrounding the gasket area, thus allowing the venting gases to escape.

The SINCGARS redesigned battery compartment used the plastic material, Xenoy, in its construction. This redesign was successful in allowing the gases from a violent venting to escape from the compartment, and in meeting all of the other requirements of the battery compartment as well. This was accomplished not just by the material used, but also by specific design elements which made proper use of these material properties. The original battery compartment was basically a five sided compartment, open on the side that fitted onto the back of the equipment. The equipment provided the sixth side of the battery compartment (see Fig. 3.1). The mere selection of the more flexible material would have accomplished little since the compartment would be prevented from flexing by the surrounding fence of the equipment joint.

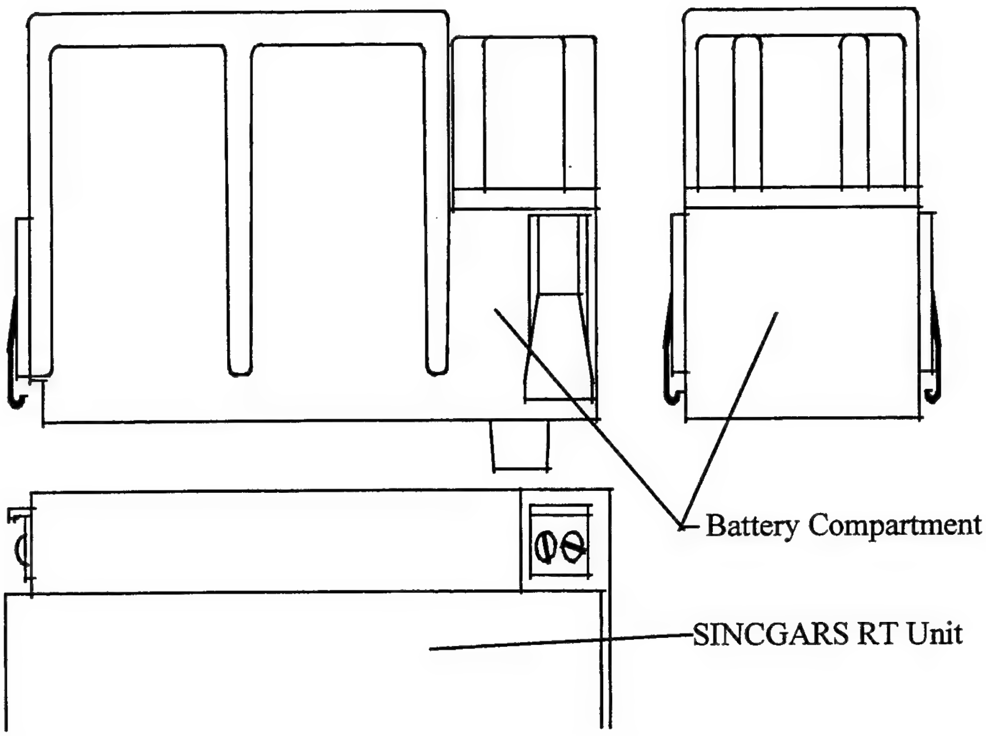


Figure 3.1. Original SINCGARS Battery Compartment Design

The redesigned battery compartment was designed as a compartment and lid assembly which was compatible with the equipment interface, but which entirely enclosed the battery itself, not using the equipment as part of the enclosure (see Fig. 3.2). The lid is quite deep, coming down over the battery approximately one third of the battery height. This results in both the compartment side and lid side at the gasketed joint being quite flexible in the direction normal to their surfaces at that point. During a violent venting, both the compartment side and the lid side flex outward (burp), separating and allowing the gases to escape through the gap between them. If the lid had been made shallow, the closeness of the top of the lid to the joint would have stiffened the lid and prevented this flexure.

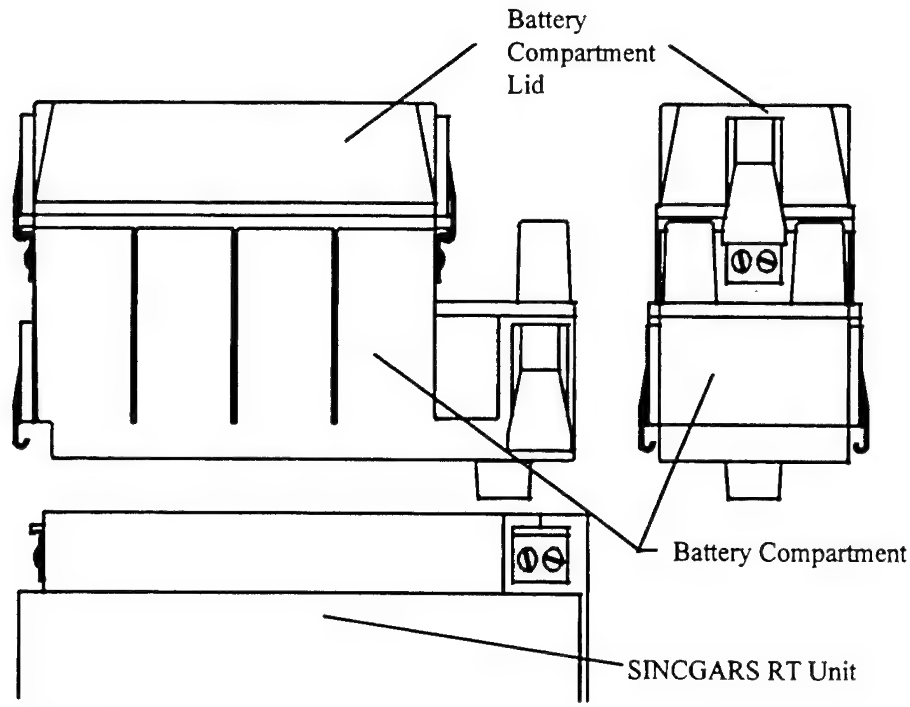


Figure 3.2. Redesigned SINCGARS Battery Compartment

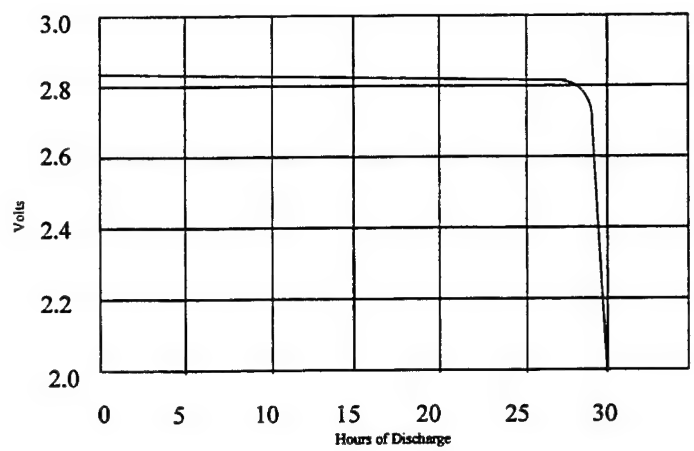
In normal operation, the joint between the compartment and lid needs to press tightly together to get good sealing action of the gasket. If the lid had been shallow, it would be more flexible in the direction of the sealing pressure, and the seal would be less reliable. With the deep lid, the lid is quite stiff in the sealing pressure direction and reliable sealing is obtained.

SECTION 4 Equipment Design to Enhance Operator Safety

This section addresses the critical aspects of equipment design as it pertains to $LiSO_2$ batteries. (Sample equipment specification input addressing battery safety requirements is provided in Appendix B, which needs to be considered when designing C-E equipment utilizing $LiSO_2$ batteries.) A properly tailored specification input addressing battery design and safety features is critical to ensure that equipment power subsystems are properly designed.

4.1 Voltage Cutoff

To prevent the battery from going into voltage reversal or forced over-discharge, which has caused a number of violent ventings, the use of an automatic voltage cutoff must be incorporated to completely shut off the equipment when the batteries no longer operate the equipment. For example, the equipment should not draw any power from the battery when the cell voltage drops below approximately 2.00 volts (see figure 4.1). In the case of the BA-5600, three-cell battery, a 6.0 volt cutoff should be implemented.



Typical discharge curve of an $LiSO_2$ cell at temperatures between 20 and 55 degrees Celsius at a C/30 discharge rate.

Figure 4.1. Typical Discharge Curve

4.2 Prevention of Lithium Explosions

Lithium explosions are of greater magnitude than violent ventings, and compliance with the test guidelines of this TB will not protect against these explosions. Lithium explosions are only known to occur as a result of charging the battery (inadvertently or otherwise). Equipment utilizing rechargeable batteries that are charged while in the equipment must be designed such that the rechargeable batteries receive a charge, while an $LiSO_2$ battery, when used, does not.

4.3 Battery and Externally Powered Equipment

The power input circuits must be designed to prevent external power from being applied to the $LiSO_2$ battery. The battery diode must never be relied upon as the sole means to prevent charging. These diodes are known to have reduced back voltages after prolonged and/or elevated temperature storage. CECOM has experienced battery explosions when partially discharged or dead batteries were charged by the reverse leakage current through the diodes, destroying the equipment and causing injury.

4.4 Lithium and Rechargeable Battery Powered Equipment

The safest approach would be to not have the capability of charging the rechargeable (secondary) batteries in the equipment to prevent inadvertent charging of the primary batteries. However, if charging in the equipment is required, additional charge protection (not relying solely on the battery diode) must be incorporated into the equipment design. External power must never be applied directly to the $LiSO_2$ battery terminals. The battery charging circuit would have to automatically stop charging after removal of the secondary battery. With the use of standard Army batteries, the addition of a mechanical means to the battery to prevent charging is not possible since these batteries may not be modified in any way.

4.5 Battery Location

It is fairly obvious that the best location for a battery compartment is on the opposite side of the equipment relative to the front panel or operator station, especially for small equipment that is held close to the operator's face or that has an eyepiece that must be looked into. In the event of a venting, to prevent SO_2 and battery fragments from hitting the operator, it is recommended that any battery compartments that must be located near the operator's face utilize hinges and open away from the operator.

SECTION 5 Test Guidelines

The objective of battery compartment testing is to apply test pressures as rapidly as possible in an attempt to closely simulate an actual violent venting. Figure 5.1 shows a representation of the test apparatus used by the U.S. Army Communications-Electronics Command (CECOM), Fort Monmouth, NJ, to perform this testing.

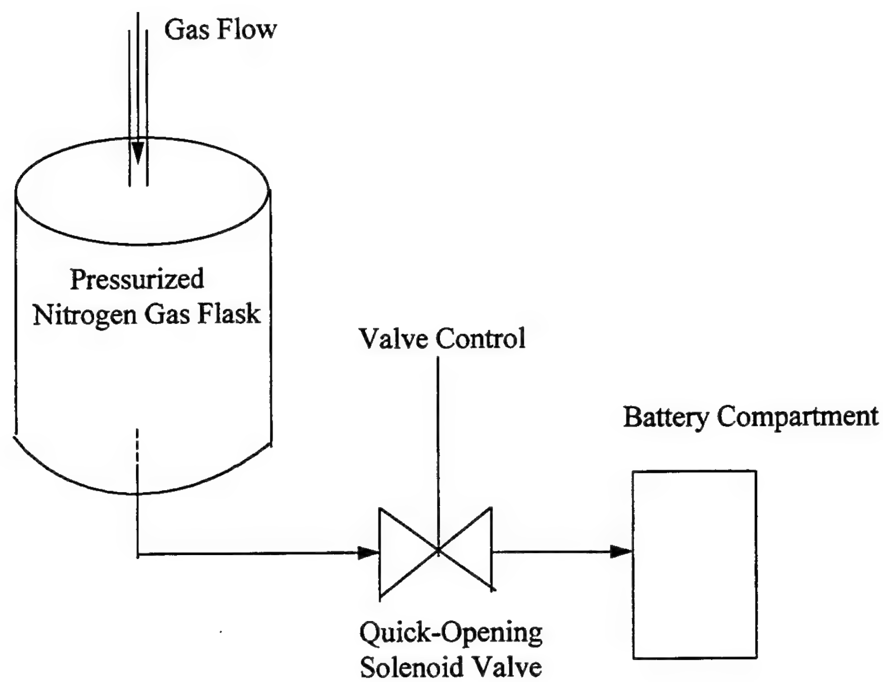


Figure 5.1 Battery Compartment Test Fixture

5.1 Test Requirements

The contractor should provide to the government for review, early in the design process, a description and detailed drawings of its proposed design of the battery compartment.

Battery compartments will be tested to 150% (safety factor) of the maximum expected pressure which would occur in the battery compartment if none of the vented gases escaped. These pressures are not actually expected to occur in a properly designed battery compartment (i.e., pressure would normally be released at a much lower pressure), but are used as a reference point against which to design and test the compartment.

The precise timing of an actual violent venting can not be measured, but is estimated to occur in less than 5 milliseconds. Therefore, the government approximates a violent venting by

injecting the entire test gas volume into the battery compartment within approximately 5 milliseconds. Because of the high pressures and hazards associated with the fracturing compartment, the whole test should be conducted within an isolated chamber to protect the testers.

The government can perform the test on any or all battery compartments at Fort Monmouth, using the test apparatus and guidelines described in this TB. Any contractor performed testing will require approval by CECOM. To obtain approval, the contractor must submit a test plan providing a complete description of their proposed test apparatus and test procedures. Approval will be based on adequacy of test equipment and instrumentation to meet the intent of this TB. The government will witness any contractor-approved testing and will determine test pass or failure based on criteria in paragraph 5.2, below. Following any successful testing, the battery compartments will become the property of the government.

5.2 Test Pass/Fail Criteria

The government will make the final determination as to whether or not a battery compartment has successfully passed the testing. The following conditions will be used to determine a test failure:

- *Shattering or the expulsion of any pieces of the battery compartment*
- *Expulsion of the test batteries*
- *The expulsion or total separation of any pressure relief plugs or panels*
- *The expulsion of any parts of the equipment interfacing the battery compartment*
- *Time required to achieve a maximum internal pressure exceeds 5 milliseconds.*

5.3 Determination of Test Pressures

Based on research at CECOM, the target pressure (P_2) of a battery compartment based on the internal free volume of the loaded (with battery installed) battery compartment (V_2), is calculated using the expression:

$$P_2\ (\text{psi}) = \frac{77{,}000*(S)}{V_2\ (\text{cm}^3)} \qquad \textbf{(Equation 5.1)}$$

Where S is a multiplication factor, which takes into account the amount of electrolyte that is available in one cell that vents. Examples are provided in Appendix C for the proper use of this equation. A table containing all pertinent data for the available types of $LiSO_2$ batteries is also included in Appendix C.

The test pressure (P_T) is 150% of the target pressure (P_2), and is expressed by the following equation:

$$P_T = 1.5*(P_2) \qquad \textbf{(Equation 5.2)}$$

5.4 Test Apparatus

As can be seen in figure 5.1, the test apparatus pressurizes the battery compartment by introducing pressurized gas from a flask (2.785 liter) through an aperture placed in one wall of the battery compartment. Figure 5.2 is a detailed schematic of the test valve used by the government to implement this test. Contractor performed testing, if approved, must utilize a test apparatus and instrumentation approved by the government.

5.4.1 Gas Insertion

Gas is injected into the battery compartment through an aperture which is positioned such that the integrity of the battery compartment is not compromised during the test. Good engineering judgment must also be exercised in designing the interface required to connect the battery compartment with the test apparatus so that the test results will not be affected. No part of the test apparatus will be permitted to attach to the test batteries. The aperture must be designed to introduce the least amount of restriction to the flow of the gases into the compartment, so that the rise time of the pressure is not adversely affected. The location of all apertures and design of the interfaces must be included on drawings to be provided to the government for review and approval. Dimensions and hole pattern of the government test apparatus interface will be provided by the government when requested.

5.4.2 Gas Distribution

A simulated or dummy battery (a battery used for testing that represents the actual solid battery volumes) will be used during testing for distribution of gases. This battery will be developed and used by the government and lent to the contractor for approved contractor testing only. Modification of this battery will not be permitted. The battery will replicate as much as possible the free volume of an actual battery. For compartments containing multiple $LiSO_2$ batteries, only one dummy battery will be used for distribution of gases. The remaining batteries will be actual solid (empty) battery cases or solid structures which will not allow any gas to enter into them during testing. Testing will be performed with the dummy battery in each of the possible battery locations. Therefore, multiple gas injection points may be necessary or additional systems must be provided to facilitate multiple tests. Any unused ports must be blocked during testing. Test batteries will NOT be secured in the battery compartment by the test apparatus. The only means of securing the battery in the compartment is by the compartment design itself.

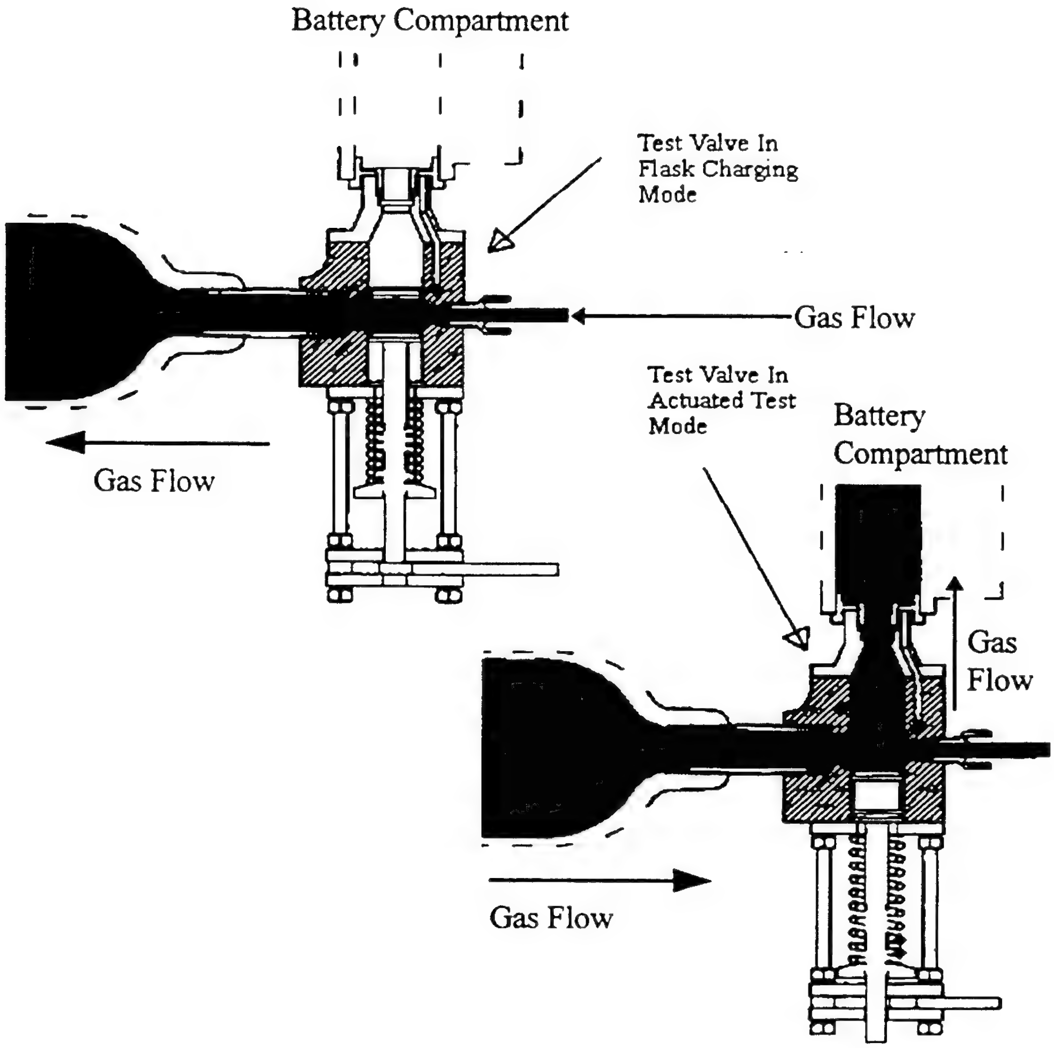


Figure 5.2. Government Test Valve

5.4.3 Flask

The test apparatus flask pressure will be higher than the test pressure to compensate for the test apparatus volumes. The following simplified expression is used to determine the flask pressure, P_{flask}:

$$P_{flask} = P_T * \frac{(V_{flask} + V_2 + V_{passages})}{V_{flask}} \quad \textbf{(Equation 5.3)}$$

Where P_T is the pressure to which the item is being tested. V_{flask} is the volume of the existing CECOM test apparatus flask, 2785 cc/170 in^3. V_2 is the volume of the loaded (battery

installed) battery compartment (same value listed in equation 5.1). $V_{passages}$ is the volume of all other test apparatus volumes (pipes, valves, etc.). See example 3 in Appendix C for the proper use of this equation using the CECOM test apparatus.

5.4.4 Pressure Transducer

Pressure versus time measurements at a point inside the battery compartment are necessary to determine if the pressure transducer has been located in the correct location. This is necessary to accurately measure the gas pressure introduced into the compartment. For example, pressure transducers located in a passage off of the inlet passage may result in an impact pressure reading of the rush of gas past the passage. This type of setup shows a compartment pressure even if no compartment is present. To determine if the pressure transducer has been properly positioned, perform the test without the battery compartment installed. If the pressure reading does not immediately drop off, then the pressure transducer is installed in the wrong location. This measurement will also verify that the gas has been injected into the battery compartment within the required 5 milliseconds.

5.5 Temperature Considerations

To accurately simulate battery ventings at the normal and worst case scenarios, all plastic battery compartments should be tested at room temperature (68 deg F) and at the upper equipment operating temperature (per equipment specification), not to exceed 130 degrees Fahrenheit. Therefore, a minimum of four plastic battery compartments must be tested (two at the upper operating temperature limit and two at room temperature). This requirement is based on the potential softening and failure of the plastic compartment and an increased chance of ventings at elevated temperatures. Testing at the low end of the operating temperature range is not necessary based on the low probability of a violent battery venting at the low temperatures. Two non-plastic battery compartments need only to be tested at room temperature. (NOTE: If more than one $LiSO_2$ battery is used in the plastic battery compartment, then additional tests must be performed with the dummy battery in each possible battery location at room temperature and at the upper operational temperature limit (not to exceed 130 deg F). For example, the use of two $LiSO_2$ batteries in one plastic battery compartment requires 8 separate tests.)

SECTION 6 Synopsis (Additional Information)

This Technical Bulletin was prepared to provide the designers of C-E systems utilizing $LiSO_2$ batteries with the necessary guidelines to design and test battery compartments that will minimize equipment damage and injury. In the event that additional information is required, it is requested that the CECOM Directorate of Safety Risk Management be contacted at the following address:

Commander
US Army Communications-Electronics Command
Fort Monmouth, NJ 07703-5024
ATTN: AMSEL-SF-SEP

Voice:
DSN: 992-0084
Commercial: (732) 532-0084

Facsimile:
DSN: 992-6403
Commercial: (732) 532-6403

MILNET:
AMSEL-SF@CECOM3.MONMOUTH.ARMY.MIL

Bibliography

References

1. TB-7, Battery Box Design Guidelines for Equipment using $LiSO_2$ Batteries, U.S. Army Communications-Electronics Command, October 1991.

2. MIL-PRF-49471, Performance Specification Sheets, Department of the Army, 2 June 1995.

3. TB 43-0134, Battery Disposition and Disposal, Department of the Army, 1 October 1996.

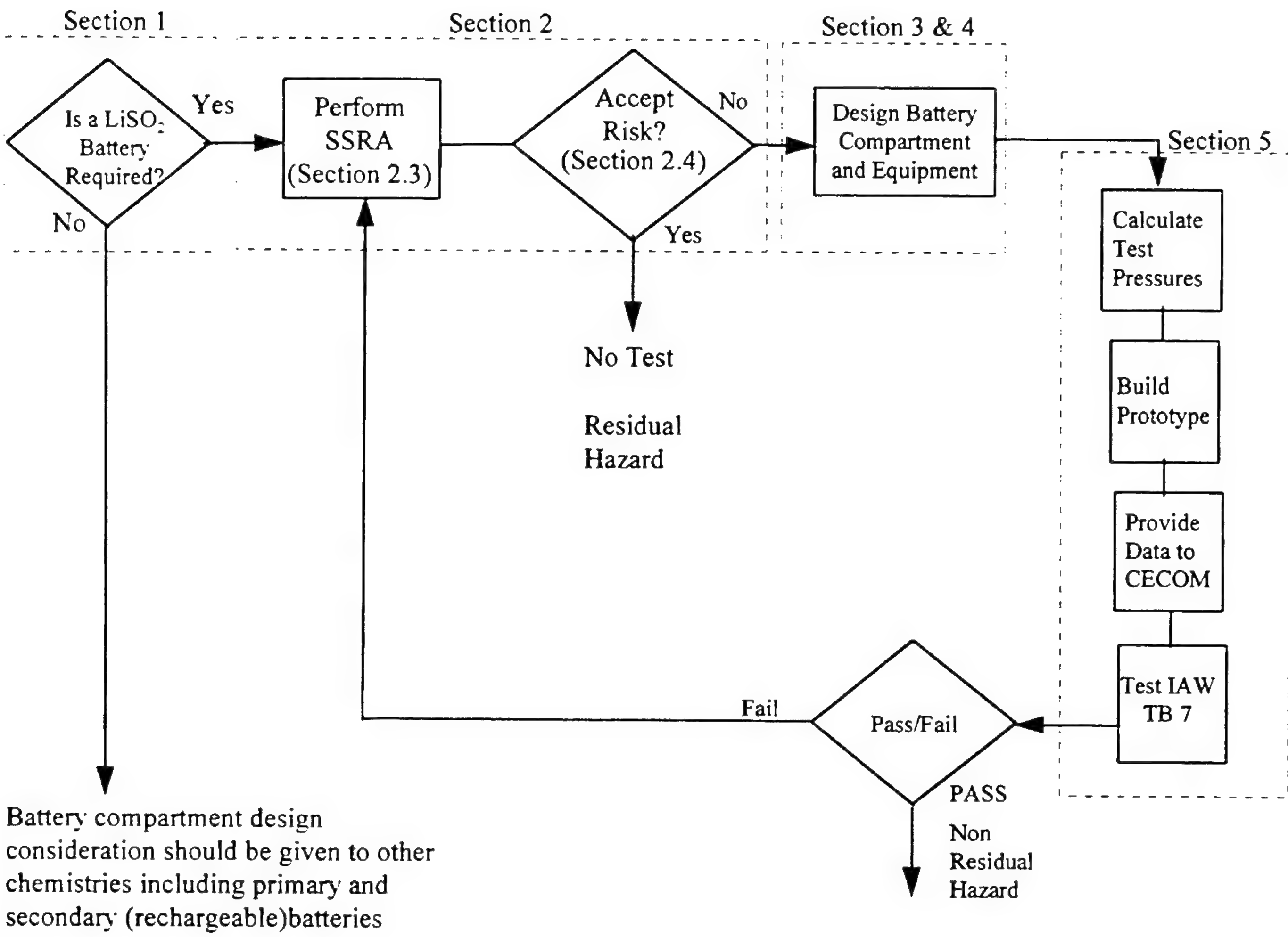
4. AR 385-16, System Safety Engineering and Management, Department of the Army, Washington, DC, 3 May 1990.

5. MIL-STD-882C, System Safety Program Requirements, 19 January 1993.

6. System Safety Risk Assessment on the Simulated Area Weapons Effects (SAWE) Multiple Laser Engagement System (SAWE/MILES II) with the BA-5590/U LiSO2 Battery, U.S. Army Communications-Electronics Command, 27 September 1995.

Appendix A

Steps in Designing and Testing $LiSO_2$ Battery Compartments



Appendix B

Sample Safety Requirements for Systems Utilizing $LiSO_2$ Batteries

The information presented in this section is intended for use in procurement data packages. Tailor this information for each individual system utilizing $LiSO_2$ batteries.

B.1. Test Requirements

The government reserves the right to test any or all battery compartments at Fort Monmouth, using the test apparatus and guidelines described in Technical Bulletin number 7, (REV A). Any battery compartments passing testing will be retained by the government.

The contractor must provide to the government for review, early in the design process, a description and drawings of their proposed design, including locations of all test apertures. The contractor must also provide a copy of test plans if contractor performed testing will be proposed. Government witnessing will be required during any contractor approved testing.

The contractor must provide to the government a total of four plastic battery compartments for each $LiSO_2$ battery required for operation. Two compartments will be tested at the upper operational temperature limit (not to exceed 130 deg F) and two at room temperature for all possible battery installation locations. Any battery compartments which utilize the equipment as part of the enclosure require that the equipment be provided for testing.

B.2. Battery Selection

The use of standard military or Commercial Off-The-Shelf (COTS) batteries is required. Battery selection for each application must be coordinated with the AMC Battery Management Office, per direction of the Army Acquisition Executive (AAE).

B.3. Sample Specifications:

B.3.1. Primary (non-rechargeable) Power Batteries

Any equipment utilizing multicell $LiSO_2$ batteries must incorporate a battery compartment to house the batteries. The $LiSO_2$ battery compartment design shall accommodate 150% of the maximum expected pressure which could be generated during a violent venting of an $LiSO_2$ battery. Test pressure data and calculations are available in the US Army CECOM Directorate of Safety Risk Management TB-7 (REV A). Equipment design shall prevent charging of $LiSO_2$ or other nonrechargeable batteries using a fail-safe design. Primary battery diodes shall not be relied upon as the sole means of preventing battery charging.

B.3.2. External Power

Primary power batteries shall be automatically disconnected when equipment is connected to external power; external power shall not be applied to the primary battery terminals. Battery power shall be automatically reconnected upon disconnect from external power. Under no circumstance shall operation of the equipment from external power require removal or replacement of the power batteries.

B.3.3. Voltage Cutoff.

A voltage cutoff must be incorporated to completely shut off the equipment when the battery voltage falls below the minimum operating voltage of the equipment. The equipment must not draw any power from the battery when the battery can no longer power the equipment.

B.3.4. Configuration Control

Any modifications made after testing of the successfully tested version of the equipment or battery compartment which may impact the battery compartment test results will require that the battery compartment to be retested follows the guidelines of TB-7 (REV A).

Appendix C
Examples

The examples is this section are intended to show how to properly implement the following equations to determine test criteria:

EQUATION 5.1 $$P_2\,(psi) = \frac{77{,}000*(S)}{V_2\,(cm^3)}$$

P_2 = Target Pressure

V_2 = Internal free volume of the battery compartment with battery installed

S = Electrolyte multiplication factor

EQUATION 5.2 $$P_T = 1.5*P_2$$

P_T = Test Pressure

P_2 = Target Pressure

EQUATION 5.3 $$P_{flask} = P_T * \frac{(V_{flask} + V_2 + V_{passages})}{V_{flask}}$$

P_{flask} = Flask Pressure

P_T = Test Pressure

V_{flask} = Flask Volume

V_2 = Internal free volume of the battery compartment with battery installed

$V_{passages}$ = Volume of test fixture and interface

EXAMPLE 1. For a battery compartment, with a total volume of 650 cc, housing one BA-5598/U, calculate the test pressure, P_T. $P_T = 1.5*P_2$.

SOLUTION 1: Using equation 5.1, solve for P_2, target pressure:

$$P_2\,(psi) = \frac{77{,}000*(S)}{V_2\,(cm^3)}$$

$V_2\ (cm^3) = V_{(compartment)} - V_{S(BA\text{-}5598)}$

$V_{(compartment)}$ = Total volume of battery compartment
$V_{S(BA\text{-}5598)}$ = Net solid volume of the BA-5598 battery (see table C.1, column 3)

Step 1. Calculate V_2

$V_2\ (cm^3) = V_{(compartment)} - V_{S(BA\text{-}5598)}$

$V_2 = 650 - 413.66 = 236.4$ cc

Step 2. Using table C.1, column 5, find S for the BA-5598/U

S=1 for the BA-5598/U.

Step 3. Calculate P_2 using equation 5.1.

$$P_2\ (psi) = \frac{77{,}000*(S)}{V_2\ (cm^3)}$$

$$P_2 = \frac{77{,}000*(1)}{236.4} = 326 \text{ psi}$$

Calculate the test pressure P_T using equation 5.2. P_T includes the 150% safety factor.

$P_T = P_2 * 1.5 =$ <u>489 PSI.</u>

EXAMPLE 2. For a battery compartment, with a total volume of 2000 cc, housing two BA-5590/U batteries, calculate the test pressure, P_T.

SOLUTION 2: The BA-5590/U battery contains ten D size cells. Assume that only one cell of one battery will open during a venting. The total volume of the second battery (table C.1, column 4) is included in the calculation in lieu of V_s of the second battery since it is assumed that the second battery will not accept any vented gas.

Using equation 5.1, solve for P_2, target pressure:

$$P_2\ (psi) = \frac{77{,}000*(S)}{V_2\ (cm^3)}$$

Table C.1. Battery Characteristics

Battery Type	*Cell Type*	*Net Solid Battery Volume* (V_S) (cc or in^3) *see note 1*	*Total Battery Volume* ($V_{battery}$) (cc or in^3) *see note 2*	*S*
BA-5590/U	D	592.2 cc/36.05 in^3	883 cc/53.9 in^3	1
BA-5590A/U	D	TBD ***see note 3***	883 cc/53.9 in^3	
BA-5598/U	Squat D	413.66/19.2	563/34.4	1
BA-5598A/U	Squat D	TBD ***see note 3***	563/34.4	
BA-5600/U	D	156.9/9.5	227/13.8	1
BA-5800/U	D	94.9/5.7	128/7.8	1
BA-5599/U	D	157.96/9.6	370/22.5	1
BA-5599A/U	D	TBD ***see note 3***	370/22.5	
BA-5847/U	D	95.2/5.75	235/14.3	1
BA-5847A/U	F	TBD ***see note 3***	235/14.3	
BA-5847B/U	D	95.2/5.75	235/14.3	1
BA-5847C/U	F	TBD ***see note 3***	235/14.3	
BA-5093/U	C	258.78/15.71	624/38	.4
BA-5093A/U	C	258.78/15.71	624/38	.4
BA-5112/U	2/3 C	56.85/3.48	162/9.9	.26
BA-5112A/U	2/3C	56.85/3.48	162/9.9	.26
BA-5557/U	2/3 C	157.51/15.82	380/23.2	.26
BA-5557A/U	2/3 C	TBD ***see note 3***	380/23.2	
BA-5567/U	1/3 C	4.05/.24	9.2/.56	.13
BA-5567A/U	1/3 C	4.05/.24	9.2/.56	.13
BA-5588/U	2/3 C	152.35/9.3	247/15.1	.26
BA-5588A/U	2/3 C	TBD ***see note 3***	247/15.1	

Notes:
1. The battery net solid volume (V_S) includes the solid volume of all cells, safety features, State of Charge meters (if applicable), Complete Discharge Devices (if applicable) and wiring, minus the free volume of a single cell (the venting cell). See figure 1.1 for those items that are included in this volume calculation.
2. The total battery volume ($V_{battery}$) is the battery volume as determined by the outside battery case dimensions.
3. Net solid volumes will be provided for these batteries when available. Calculation of test pressures of battery compartments utilizing batteries with multiple versions shall utilize the largest net solid battery volume in that group (version), unless approved by CECOM.

$V_2\ (cm^3) = V_{(compartment)} - V_{S(BA\text{-}5590)} - V_{battery(BA\text{-}5590)}$

Step 1. Solve for V_2

$V_2\ (cm^3) = V_{(compartment)} - V_{S(BA\text{-}5590)} - V_{battery(BA\text{-}5590)}$

$V_2 = 2000 - 592.2 - 883 = 524.8$ cc.

NOTE: The net solid volume of the battery with the vented cell and total volume of the second battery (battery without the vented cell) are included in this calculation since the second battery will not accept the instantaneous gas generated during a violent venting.

Step 2. Using table C.1, column 5, find S for the BA-5590/U

S=1 for the BA-5590

Step 3. Calculate P_2

$$P_2\ (psi) = \frac{77{,}000*(S)}{V_2\ (cm^3)}$$

$$P_2 = \frac{77{,}000*(1)}{524.8} = 146.7 \text{ psi}$$

Including the 150% safety factor, the test pressure, $P_T = P_2 * 1.5 =$ <u>220 PSI.</u>

EXAMPLE 3. Determine the flask test pressure (P_{flask}) of the battery compartment tested in example 1, above.

Using equation 5.3,

$$P_{flask} = P_T * \frac{(V_{flask} + V_2 + V_{passages})}{V_{flask}}$$

SOLUTION 3: For the battery compartment in example 1, the test pressure (P_T) was calculated to be 489 psi. V_{flask} is the volume of the CECOM test apparatus flask (2785 cc/170 in^3). V_2 is the battery compartment free volume calculated in example 1 (236.4

cc). $V_{passages}$ is the unpressurized volume of the test fixture and the interface (26 cc/1.59 in^3).

$$P_{flask} = P_T * \frac{(V_{flask} + V_2 + V_{passages})}{V_{flask}}$$

P_{flask} = (489 * (2785+236.4+26))/2785 = 535 psi. Thus, a flask test pressure of 535 psi, is required to reach a test pressure of 489 psi.

EXAMPLE 4. Calculate the test pressure of a battery compartment utilizing one cylindrical BA-5800/U battery with a total battery compartment volume of 150 cc. Also, calculate the test pressure when (a) the battery compartment is enlarged by 25 cc and (b) when the internal free volume of the equipment is taken into consideration to accept the vented gas. Assume that the internal free volume of the equipment is 280 cc.

SOLUTION 4:

From equation 5.1,

$$P_2 \text{ (psi)} = \frac{77{,}000*(S)}{V_2 \text{ (cm}^3\text{)}}$$

Step 1. Solve for V_2.

V_2 (cm^3)= $V_{(compartment)}$ - $V_{S(BA\text{-}5800)}$ = 150 - 94.9 = 55.1 cc

Step 2. Using table C.1, column 5, find S for the BA-5800/U

S=1 for the BA-5800

Step 3. Solve for P_2

$$P_2 \text{ (psi)} = \frac{77{,}000*(S)}{V_2 \text{ (cm}^3\text{)}}$$

$$= \frac{77{,}000(1)}{55.1} = 1397 \text{ psi}$$

Including the 150% safety factor, the test pressure = P_2 * 1.5 = 2096 PSI

Step 4. Since a costly equipment design may be required to accommodate the high test pressures, modification to the battery compartment may be necessary. There are two ways in which the battery compartment could be redesigned: (a) enlarge the battery compartment, and/or (b) utilize the equipment free volume to vent the gases into.

(a) Enlarging the battery compartment by 25 cc (to 175 cc) will lower the test pressure in the following manner:

$V_2 = V_{(compartment)} - V_{S(BA\text{-}5800)} = 175 - 94.9 = 80.1$ cc

$$P_2\,(psi) = \frac{77{,}000*(S)}{V_2\,(cm^3)}$$

$$= \frac{77{,}000(1)}{80.1} = 961 \text{ psi}$$

P_T= 150% of 961 = 1441.5 psi

(b) Utilizing the internal free volume of the equipment (280 cc) will lower the test pressure in the following manner:

$V_2 = V_{(compartment)} - V_{S(BA\text{-}5800)} + V_{free\ (equipment)} = 150 - 94.9 + 280 = 335.1$ cc, then P_2 = 77,000/335.1 = 230 psi. With the 150% safety factor, the test pressure = 1.5 * 230 = 345 psi.

Utilizing the internal free volume of the equipment appears to be the better choice. However, caution must be used to ensure that this design change does not introduce any new hazards to the system. If the system uses glass or plastic displays or optics, these components must be protected to ensure they do not present a more severe hazard to personnel in the event of a violent venting. Any configuration changes to the equipment that could impact the flow of gases or reduce the available free volume would require the equipment and battery compartment to be retested.